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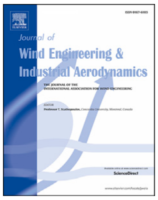

Assessing methods to extrapolate the vertical wind-speed profile from surface observations in a city centre during strong winds

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ABSTRACT

Knowledge of the vertical wind-speed profile in cities is important for the construction and insurance industries, wind energy predictions, and simulations of pollutant and toxic gas release. Here, five methods to estimate the spatially- and temporally-averaged wind-speed profile are compared in London: the logarithmic wind law (*LOG*); the Deaves and Harris equilibrium (DH_e) and non-equilibrium (DH_v) models; an adaptation of the power law (*PL*) and the Gryning et al. (*GR*) profile. Using measurements at 2.5 times the average building height, a source area model is used to determine aerodynamic roughness parameters using two morphometric methods, which assume homogeneous and variable roughness-element heights, respectively. Hourly-averaged wind speeds are extrapolated to 200 m above the canopy during strong wind conditions, and compared to wind speeds observed with Doppler lidar. Wind speeds are consistently underestimated if roughness-element height variability is not considered during aerodynamic parameter determination. Considering height variability, the resulting estimations with the DH_e and *GR* profiles are marginally more similar to observations than the DH_v profile, which is more accurate than the *LOG* and *PL* methods. An exception is in directions with more homogeneous fetch and a gradual reduction in upwind roughness, where the *LOG* and *PL* profiles are more appropriate.

1. Introduction

Modelling the wind-speed profile in the lowest few hundred metres of the urban boundary layer (UBL) is becoming increasingly important. The rapid development of urban areas is resulting in taller buildings with unique forms and arrangements which the construction and insurance industries need to account for (Petrini and Ciampoli, 2012; Tanaka et al., 2012; Taranath, 2016). The threat of pollutant and hazardous material release (accidental and terror related) is increasingly being realized (Belcher, 2005; Tominaga and Stathopoulos, 2016), and widespread city-based renewable wind energy is being explored (Millward-Hopkins et al., 2013; Ishugah et al., 2014; Emejeamara et al., 2015). Accurate vertical profiles of wind-speed are essential boundary conditions to physical (i.e. wind tunnel) and numerical (e.g. computational fluid dynamics) models, as the final results are sensitive to these initial conditions (e.g. Schultz et al., 2005; Ricci et al., 2016). Critical questions which remain include: how well can the spatially- and temporally-averaged urban boundary layer winds be estimated, what are the minimum input requirements, and what are the associated uncertainties?

Over flat, homogeneous terrain with extensive fetch, a dynamic equilibrium between strong winds and the surface roughness is reached, which is well understood and modelled quantitatively (Harris and Deaves, 1980). However, flat homogeneous fetch is rare in urban areas. There are often distinct changes in surface cover in close proximity, characterised by different land cover types and roughness elements of different form (e.g. height variability, density). The structure of the UBL is therefore highly variable because of the numerous sources and sinks of heat and momentum (Gryning et al., 2011), which means that modelling the wind-speed profile is challenging.

The UBL is traditionally divided into several distinct layers (e.g. Fernando, 2010; his Fig. 9), the location of which is determined by surface morphology and mesoscale conditions (Barlow, 2014). The urban canopy layer (UCL) is where surface roughness elements such as buildings are located (Oke, 2007) and is associated with highly variable flow. The UCL is within the roughness sublayer (RSL) (Roth, 2000), the depth of which is typically 2–5 times the average roughness-element height (H_{av}) (Roth, 2000; Barlow, 2014), varying with the roughness-element density (Raupach et al., 1991; Grimmond and Oke, 1999; Roth, 2000;

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Oke, 2007; Barlow, 2014), staggering (Cheng and Castro, 2002) and height variability (Cheng and Castro, 2002). Between the RSL and approximately 10% of the boundary layer depth is the inertial sublayer (ISL), where the flow becomes free of the wakes associated with individual roughness elements. If the airflow is fully adapted to upwind roughness elements in the ISL, a horizontally homogeneous flow is observed (Barlow, 2014) and it is therefore possible to determine a spatially- and temporally-averaged wind-speed profile.

This paper assesses how well the wind-speed profile can be modelled using surface observations at a reference site in central London, United Kingdom. The aerodynamic roughness parameters of the zero-plane displacement (z_d) and aerodynamic roughness length (z_0) are determined using two morphometric methods (i.e. from surface form). One morphometric method assumes homogeneous roughness elements (Macdonald et al., 1998; *Mac*), the other considers their height variability (Kanda et al., 2013; *Kan*). Five different methods are then used to extrapolate the wind speed to 200 m above the canopy. These wind speeds are compared to those observed using Doppler lidar.

Specifically, the methods considered are: the logarithmic wind law (Blackadar and Tennekes, 1968) (*LOG*); the Deaves and Harris equilibrium (DH_e) and non-equilibrium (DH_v) models (Deaves and Harris, 1978; Harris and Deaves, 1980); an adapted power law which directly considers surface roughness (Sedefian, 1980) (*PL*) and a profile proposed by Gryning et al. (2007) (*GR*) (see Section 2 for the selection of methods). Analysis is undertaken for neutral conditions, to allow the accuracy of extrapolated profiles during 'ideal' conditions to be understood first, without the additional uncertainties associated with thermal effects (e.g. Högström, 1996).

2. Describing the boundary layer wind speed using surface observations

In addition to the models named above, other methods to describe the spatially- and temporally-averaged wind-speed profile have been derived (Wieringa, 1986; Etling, 2002; Wilson and Flesch, 2003, Emeis et al., 2007; Peña et al., 2010; Yang et al., 2016). Wieringa's (1986) two-layer model requires definition of the height above which the logarithmic wind law (*LOG*) becomes inappropriate. Given that it is both difficult to determine this height in the UBL (e.g. Roth, 2000; Barlow, 2014) and the performance of the *LOG* method is assessed in this study, Wieringa's (1986) method and the two-layer model of Wilson and Flesch (2003) are not considered here. Emeis et al. (2007) developed Etling's (2002) multi-layer model to incorporate the effects of atmospheric stability. As with Wieringa's (1986) model, the applicable height range of *LOG* is required. Additionally, the method requires the geostrophic wind speed (as well as surface measurements) and is therefore not considered here. For similar reasons the Yang et al. (2016) model is not considered. Peña et al. (2010) use Gryning et al.'s (2007) mixing length model with a variety of mixing length parameterisations. However, there is no conclusive evidence that any of the assessed parameterisations provide improved accuracy for wind-speed estimation, therefore only the original formulation of Gryning et al. (2007) is used.

For simplicity, the following assumptions are typically made when modelling the neutral wind-speed profile in the atmospheric boundary layer (e.g. Garratt, 1992): (i) stationarity, (ii) horizontal homogeneity, (iii) a barotropic atmosphere, where density is a function of pressure only, and (iv) uniform roughness with an extensive fetch and no subsidence, therefore there is no mean vertical component of the wind. These assumptions are inherent in each of the five methods assessed here, however DH_v does not assume uniform upwind roughness (assumption iv).

Observations of the vertical wind profile are becoming increasingly available in urban areas (e.g. Tamura et al., 2001; Allwine et al., 2002; Emeis, 2004; Frehlich et al., 2006; Emeis et al., 2007; Drew et al., 2013; Tan et al., 2015; Liu et al., 2017). Especially because remote sensing techniques, such as lidar and sodar, overcome the impracticalities associated with *in-situ* tower mounted (Al-Jiboori and Fei, 2005) or tethersonde (Tsuang et al., 2003) observations. Lidar is often favoured to sodar in urban areas, due to the noisiness of the latter. However, both have been used to assess the structure of the UBL (Barlow et al., 2008, 2011) and associated wind flow (Drew et al., 2013; Lane et al., 2013; Wood et al., 2013; Kent et al., 2017a). Specifically in London, wind speeds observed with Doppler lidar have been used to assess how accurately wind speeds can be: translated from a 'rural' airport site to central London (Drew et al., 2013); and, estimated using the logarithmic wind law extrapolated from observations at approximately 2.5 times the canopy height, using a range of methods to determine z_d and z_0 (Kent et al., 2017a). Here this work is further developed by considering wind directions with a more complex fetch, as well as different methods to extrapolate the wind-speed profile. A source area footprint model is used to estimate the upstream effective roughness.

2.1. The logarithmic wind law

The logarithmic wind law (*LOG*), may be derived through: (i) matching a region where the velocity gradients determined from equations obeying the upper and lower boundary conditions of ABL flow are the same (also termed asymptotic similarity theory); or (ii) eddy viscosity, or k-theory. The derivation demonstrates that for a height, z, if the flow is aligned to the wind direction, the mean wind speed $\overline{U}(z)$ during neutral atmospheric stability can be determined by (Blackadar and Tennekes, 1968; Tennekes, 1973):

$$\overline{U}(z) = \frac{u_*}{\kappa}\ln\left(\frac{z - z_d}{z_0}\right) \tag{1}$$

where u_* is the friction velocity and κ is von Karman's constant. Following full scale field observations which indicate $\kappa = 0.38$–0.42 and scaled experiments in wind tunnels indicating $\kappa = 0.4$ (Garratt, 1992), a value of $\kappa = 0.4$ is used in this work. The zero-plane displacement (z_d) is the vertical displacement of the wind-speed profile due to surface roughness elements and has been demonstrated to correspond to the 'drag centroid' of the surface, or the height at which mean drag appears to act (Jackson, 1981). The aerodynamic roughness length (z_0) is the height at which wind speed becomes zero in the absence of z_d. Theoretically, *LOG* applies in the ISL, where flow is free from individual roughness-element wakes, but still scales with surface length scales only (z_d and z_0). However, it has been shown to be applicable both close to roughness elements (Cheng and Castro, 2002) and for a considerable depth of the boundary layer (Macdonald et al., 2000; Castro et al., 2006; Cheng et al., 2007; Kent et al., 2017a).

2.2. Adapted power law profile

The power law provides a relation between mean wind speeds ($\overline{U}(z_1)$, $\overline{U}(z_2)$) at two different heights (z_1, z_2), with a wind shear exponent (α_{PL}) describing fetch characteristics:

$$\overline{U}(z_1) = \overline{U}(z_2)\left(\frac{z_1 - z_d}{z_2 - z_d}\right)^{\alpha_{PL}} \tag{2}$$

The exponent, α_{PL} (between 0 and 1), provides a best fit of wind speeds between the two heights and is proportional to the vertical gradient of wind speed with height. Typically, a single value of α_{PL} is used for different surfaces (e.g. Davenport, 1960), which does not allow the exponent to vary with height, stability or directly consider surface roughness (Irwin, 1979; Emeis, 2014). Sedefian's (1980) alteration of the exponent addresses this, and is used here:

$$\alpha_{PL} = \frac{\phi_m\left(\frac{z}{L}\right)}{\left[\ln\left(\frac{z}{z_0}\right) - \Psi_m\left(\frac{z}{L}\right)\right]} \tag{3}$$